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EVALUATION OF A FLUIDIC OSCILLATOR AS A MOLECULAR-WEIGHT SENSOR FOR GAS MIXTURES

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Cleveland, Ohio

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ABSTRACT

A fluidic oscillator was tested to determine its performance as a molecular-weight sensor for flowing gas mixtures. A linear relation between inverse frequency squared and molecular weight was obtained over the test range. It was also determined that the temperature of the gas and pressure drop across the oscillator must be kept constant.

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SUMMARY

A fluidic oscillator was tested to investigate its characteristics as a sensor to detect small changes in molecular weight in a flowing gas mixture. Gas mixtures of (1) hydrogen and nitrogen, and (2) helium and xenon were analyzed. A linear relation between molecular weight and inverse frequency squared was obtained over the range tested. The effect of changes in temperature and pressure on oscillator frequency was investigated, and it was concluded that pressure and temperature must remain constant for accurate sensing of molecular weight.

INTRODUCTION

Gas mixtures are being considered as the working fluid in closed-cycle space power generation systems to increase cycle efficiency (ref. 1). But the molecular weight of a gas mixture could change during operation and affect the overall efficiency and performance of the system. To detect any changes in molecular weight of the gas mixture, a measuring device or sensor is needed that will continuously indicate the molecular weight of the gas. For applications in space, the device should be highly reliable, compact, and have a simple output signal.

An experimental investigation was conducted to examine a fluidic oscillator as a molecular-weight sensing device that will detect small changes in molecular weight for flowing gas mixtures. Tests were conducted with a fluidic oscillator developed by the Research Laboratories Division of the Bendix Corporation as a humidity sensor for Lewis Research Center (ref. 2). A diatomic gas mixture of hydrogen and nitrogen was experimentally investigated over a molecular weight range of 3.4 to 6.8, and a monatomic gas mixture of helium and xenon over a molecular weight range of 31.5 to 44.9.

During these tests, temperature and pressure drop across the oscillator were held constant. Using nitrogen gas, the effect of changes in pressure on output frequency was determined.

APPARATUS AND TEST PROCEDURE

The oscillator tested is a fluidic bistable amplifier in which part of the output flow is fed back to the control ports (fig. 1). A fluidic oscillator (refs. 3 and 4) operates on the principle that the frequency of oscillation of a pressure pulse propagating through a feedback loop at sonic velocity is inversely proportional to the square root of molecular weight of the gas mixture at constant temperature.

A schematic diagram of the test rig used to test the oscillator is shown in figure 2. This is basically the same test rig that was used in reference 2.

Test were conducted at ambient temperature. The flow rates of the gases were independently measured by using calibrated orifices in the "choked" condition for which flow is proportional to upstream pressure. Pressure transducers were used to measure pressure upstream of the orifices and were calibrated before each test. Flow of each gas was regulated by control valves, and the two gases were mixed before flowing through the fluidic oscillator. The pressure drop across the fluidic oscillator was kept constant by regulating the bypass flow valve (automatic control). The frequency of oscillation was recorded by a piezoelectric pressure transducer connected to a charge amplifier and read out on an electronic counter. Molecular weight of the gas mixture was calculated from the measured flow rates.

Additional tests were run with nitrogen gas at ambient temperature in order to determine the effect of changes in pressure drop and total pressure on oscillator frequency at constant molecular weight and temperature. Pressure drop across the oscillator was varied from 3.5 to 7.0 psi (2.4×10^4 to 4.8×10^4 N/m^2) by varying the bypass flow (gas exhausting to atmosphere after leaving oscillator). A hand valve and pressure gage were installed in the exhaust system; by regulating the hand valve, a back pressure of 17.7 psia (1.2×10^5 N/m^2) was maintained while pressure drop across the oscillator was varied from 5.0 to 7.0 psi (3.4×10^4 to 4.8×10^4 N/m^2).

RESULTS AND DISCUSSION

Relation of Frequency to Small Changes in Molecular Weight

The relation between inverse-frequency squared and molecular weight was determined for a mixture of diatomic gases and a mixture of monatomic gases. Figure 3 shows this relation for the mixture of the diatomic gases hydrogen and nitrogen over a molecular weight range of 3.4 to 6.8. The tests were conducted at constant temperature of 70° F (21° C) and with constant pressure drops of 6.0 and 7.0 psi (4.1×10^{4} and 4.8×10^{4} N/m^{2}) across the oscillator.

Figure 4 shows inverse frequency squared against molecular weight for a mixture of the monatomic gases helium and xenon. The molecular weight was varied from 31.5 to 44.9 at a constant temperature of 70° F (21° C) and with a constant pressure drop of 5.0 psi (3.4×10^{4} N/m^{2}) across the oscillator.

As expected from theoretical considerations (see appendix A), the experimental data show a linear relation over the two ranges of molecular weight tested. When the curve in figure 3 is extended, it does not coincide with the curve in figure 4. This could be attributed to the following factors. First, the specific heat ratio of the monatomic gases is 1.67 while the diatomic gases have a specific heat ratio of 1.40. Since changes in specific heat ratio affect sonic velocity, frequency of oscillation will also be affected. Second, the tests were conducted with different pressure drops across the oscillator. The effect of pressure drop on oscillator frequency is explained later. Third, the average viscosity of the helium-xenon gas mixture is greater than the viscosity of the hydrogen-nitrogen mixture. This difference in viscosity causes a sizeable difference in Reynolds number thus affecting the gas stream velocity and frequency of oscillation.

Sensitivity and Linearity of Sensor

A plot of output frequency against molecular weight for a gas mixture of helium and xenon is shown in figure 5 using the same test points as in figure 3. A straight line through 70 percent of the range tested represents a change in molecular weight from 33.5 to 42.9 or ±12.3 percent from the mean molecular weight of 38.2. It can be seen that the maximum deviation in this linear approximation between output frequency and molecular weight is less than 0.5 percent. Over this range, frequency varied from 603 to 543 hertz for an average sensitivity of 6.4 hertz per unit of molecular weight.

A linear approximation can also be obtained for the hydrogen-nitrogen gas mixture over a ±12 percent change in molecular weight. Figure 6 shows frequency against molecular weight with a straight line approximation using a mean molecular weight of 5.1. Since the frequency range is higher and the molecular weight range is lower, the average sensitivity over the linear range is 130 hertz per unit of molecular weight.

Effect of Pressure and Temperature Changes on Frequency

The curves presented in figure 3 indicate that there is a significant pressure effect on output frequency. This was investigated for nitrogen. Figure 7 shows the effect of changes in pressure on frequency when nitrogen gas (molecular weight of 28) at constant temperature of 70° F (21° C) flows through the oscillator. The test results clearly show that the oscillator has a greater sensitivity to changes in pressure drop than to equivalent changes in pressure level over the range tested. For a 3.0 psi (2.1×10^4 N/m^2) change in pressure drop from 4.0 to 7.0 psi (2.8×10^4 to 4.8×10^4 N/m^2), the frequency varied from 627 to 703 hertz. But for a 3.0 psi (2.1×10^4 N/m^2) change in inlet and exhaust pressure, the average frequency change was only 4 hertz. The curve also shows the nonlinearity of changes in pressure drop to changes in frequency. For a change in pressure drop from 4.0 to 5.0 psi (2.8×10^4 to 3.4×10^4 N/m^2), a frequency change of 31 hertz was observed, but a change in pressure drop from 6.0 to 7.0 psi (4.1×10^4 to 4.8×10^4 N/m^2) produced only a frequency change of 19 hertz. From the above analysis it can be theorized that as the pressure drop across the oscillator changes, jet velocity of the flowing gas changes, which in turn affects the propagation of the pressure pulse in the flowing fluid. But additional factors such as the change in energy of the propagated pressure pulse need to be included since Reynolds number also changes with jet velocity.

Thus, for accurate molecular weight readings, the pressure drop across the oscillator and inlet supply pressure must remain constant.

In addition to the pressure effect, the oscillator is sensitive to temperature. The pressure pulse propagates through the feedback duct at sonic velocity. Assuming that the gas mixtures obey the perfect gas law, changes in absolute temperature are inversely proportional to molecular weight and thus directly proportional to frequency squared. Thus, for accurate measurements of molecular weight, the temperature of the flowing gas must be held constant or temperature calibration applied to the output.

SUMMARY OF RESULTS

A fluidic oscillator was tested to determine its feasibility as a molecular weight sensor of flowing gas mixtures for small changes in molecular weight. The following results were obtained:

1. A linear relation was obtained between molecular weight and inverse frequency squared for a gas mixture of hydrogen and nitrogen and a gas mixture of helium and xenon at constant temperature and pressure over the range tested.

2. For accurate measurements of molecular weight, pressure and temperature of the flowing gas must remain constant.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 23, 1968,
120-27-03-42-22.

APPENDIX - THEORETICAL ANALYSIS OF A FLUIDIC OSCILLATOR

A fluidic oscillator is a bistable element with feedback to cause switching of the main jet (fig. 1). When the gas jet, issuing from the nozzle, switches from one putput port to the other, a sonic pressure pulse is produced at the nozzle. This pulse propagates through the gaseous media in the feedback duct at the speed of sound. Assuming "perfect gas" conditions, the velocity of sound (v_c) is a function of specific heat ratio (k), pressure (P), and density (ρ).

$$v_c = \sqrt{\frac{kP}{\rho}}$$

Also, for a perfect gas, $P = \rho RT/M$ where R is the universal gas constant, T is the absolute temperature, and M is the molecular weight. Thus:

$$v_c = \sqrt{\frac{kRT}{M}} \tag{1}$$

The time required for a pressure pulse to travel through one feedback duct is equal to length of travel (l) divided by pulse velocity (v_c). Since the main jet alternates from one side to the other side during a complete cycle, the frequency of oscillation (f) can be obtained from the relation:

$$f = \frac{v_c}{2l} \tag{2}$$

Substituting equation (1) into equation (2):

$$f = \frac{1}{2l}\sqrt{\frac{kRT}{M}}$$

Squaring both sides and taking the reciprocal:

$$\frac{1}{f^2} = \frac{4l^2M}{kRT} \tag{3}$$

At constant temperature and constant specific heat ratio of the gas, the equation can be reduced to:

$$\frac{1}{f^2} = CM$$

where

$$C = \frac{4l^2}{kRT}$$

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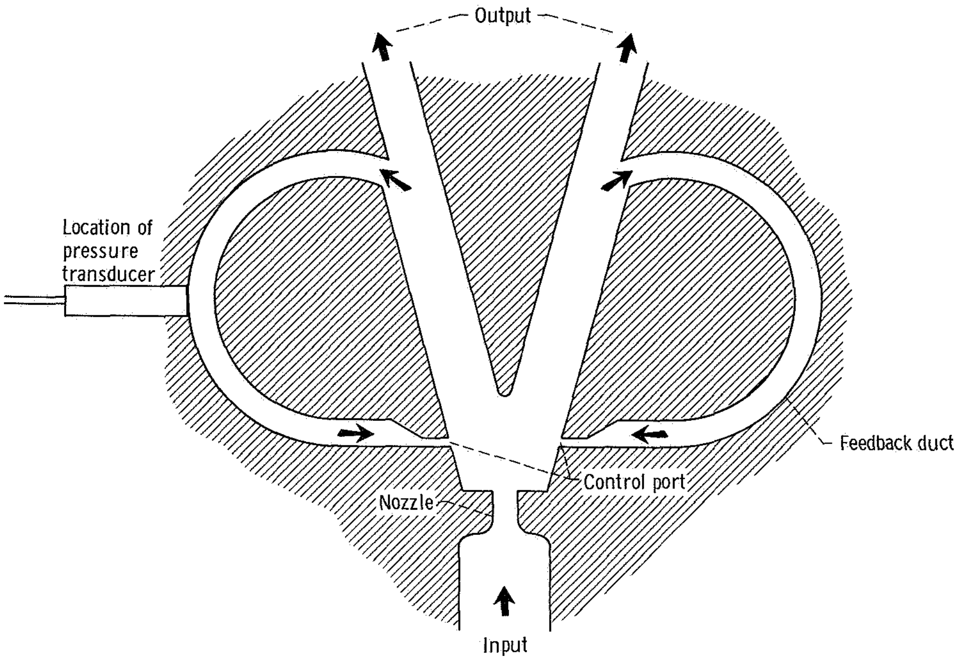

Figure 1. - Fluidic oscillator.

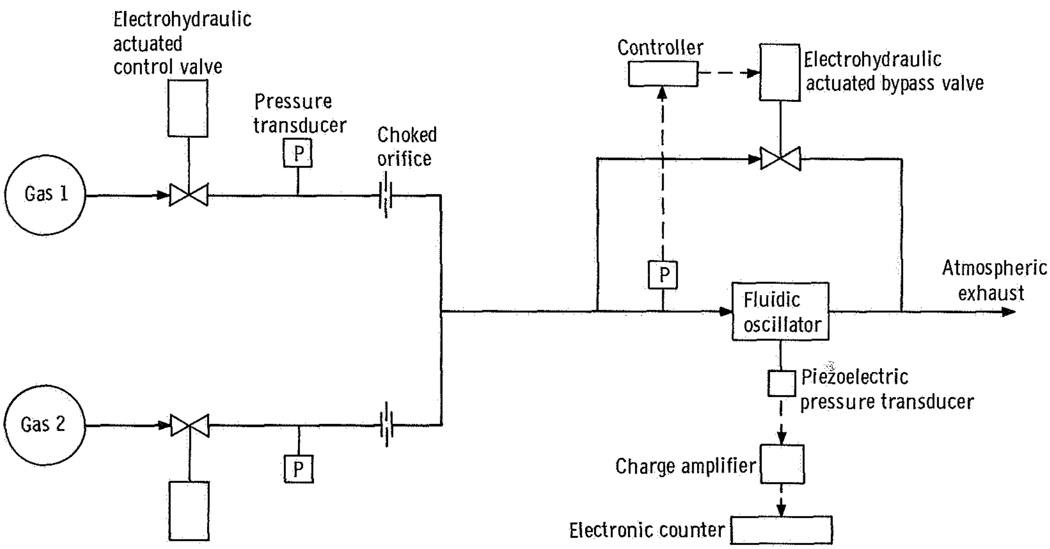

Figure 2. - Test rig.

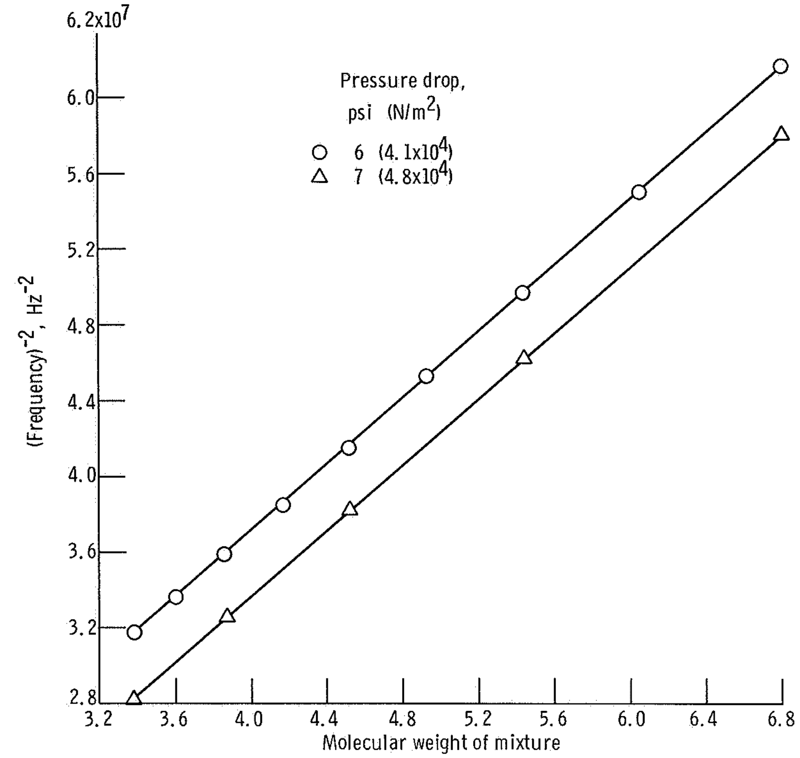

Figure 3. - Oscillator frequency for mixtures of hydrogen and nitrogen at 70° F (21° C).

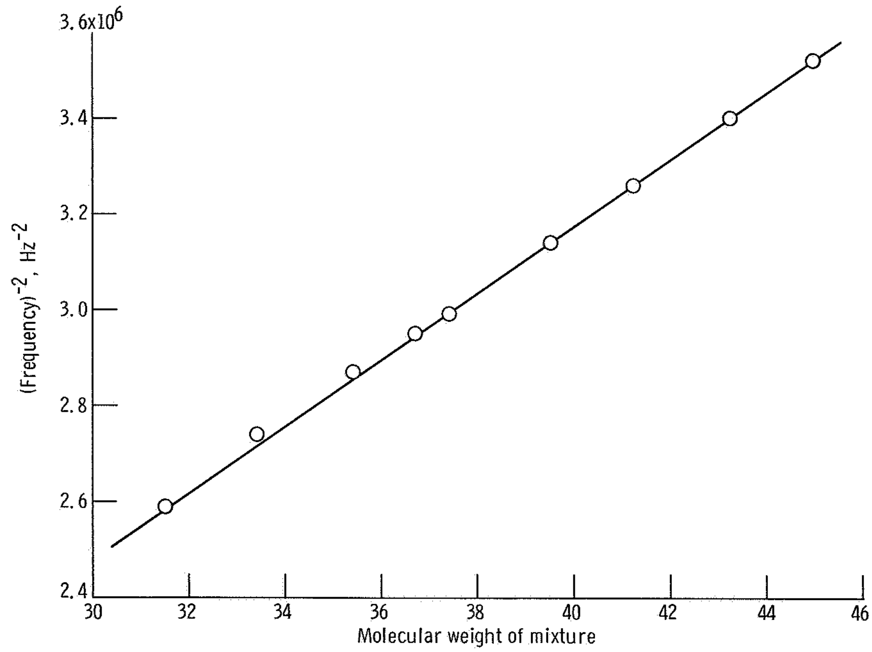

Figure 4. - Oscillator frequency for mixtures of helium and xenon at 70° F (21° C).

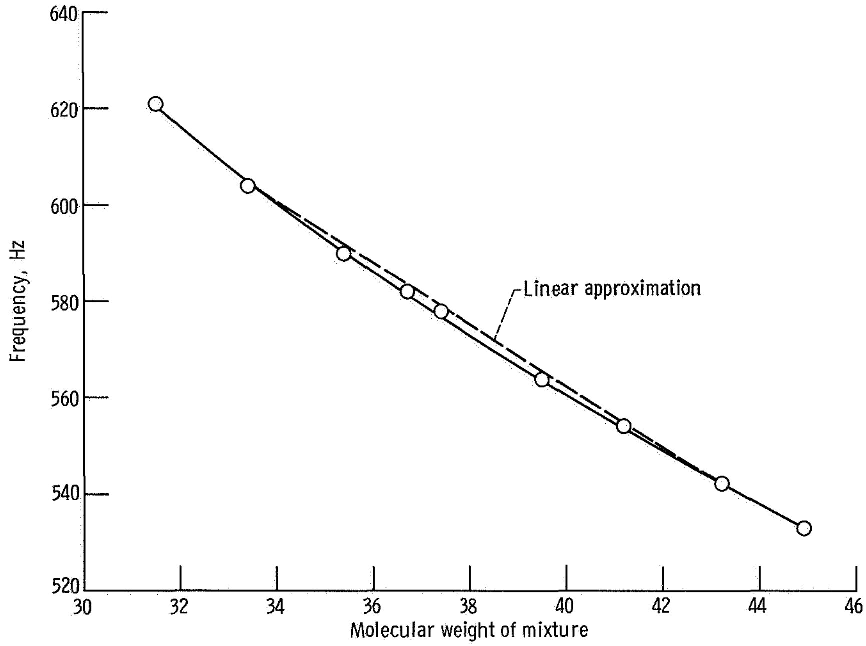

Figure 5. - Direct relation of oscillator frequency to molecular weight of helium, xenon mixture at 70° F (21° C) and at pressure drop of 5 psi (3.4×10^4 N/m^2).

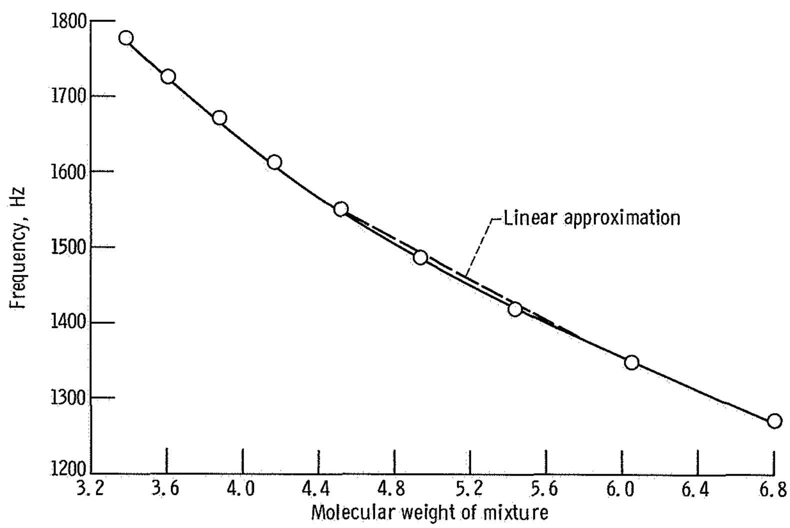

Figure 6. - Direct relation of oscillator frequency to molecular weight of hydrogen, nitrogen mixture at 70° F (21° C) and pressure drop of 7 psi (4.8×10^4 N/m^2).

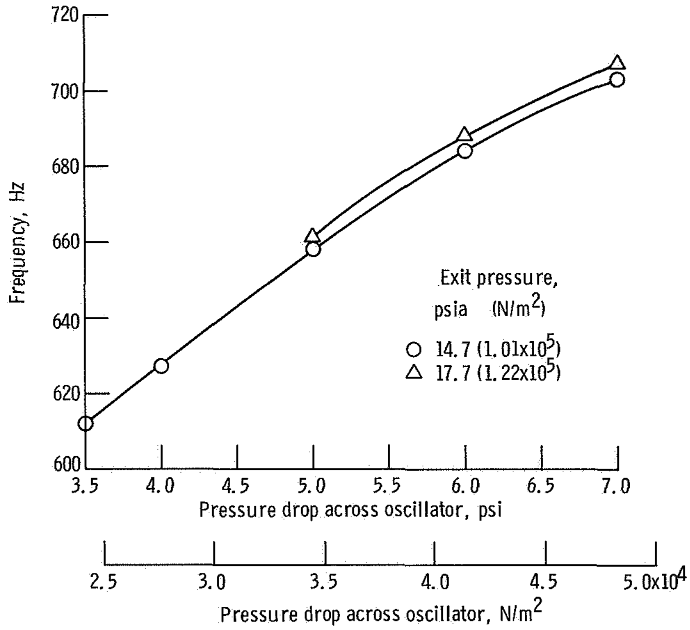

Figure 7. - Effect of changes in pressure on oscillator frequency during flow on nitrogen, at 70° F (21° C) through oscillator.

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